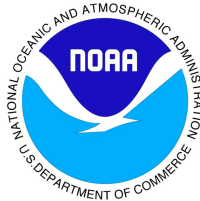




Synthetic Aperture Radar Marine User's Manual

Washington, DC
September 2004

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
Office of Research and Applications



Synthetic Aperture Radar Marine User's Manual

Christopher R. Jackson
John R. Apel
Editors

September 2004

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

National Oceanic and Atmospheric Administration
Vice Admiral Conrad C. Lautenbacher, Jr., U.S. Navy (Ret.), Under Secretary

National Environmental Satellite, Data, and Information Service
Gregory W. Withee, Assistant Administrator

Office of Research and Applications
Marie C. Colton, Director

**IN MEMORY OF
JOHN R. APEL
(1930 – 2001)**



This Manual is dedicated to Dr. John Ralph Apel who conceived of its creation. The “Father” of SEASAT was a pioneer in the use of remote sensing, in particular synthetic aperture radar (SAR), for investigating the physics of the sea. John believed the key to the wide spread acceptance of SAR was in educating potential users to its benefits. It was a great loss in creating this Manual not to be able to fully take advantage of John’s 40 years of experience. Those who knew and worked with John found him to be a dedicated researcher, a visionary leader and a delightful companion. We will miss him.

ACKNOWLEDGEMENTS

The Editors want to express their gratitude to the many people who made this Manual possible. First and foremost are the Manual's authors who spent a considerable amount of time preparing and revising their material. Many authors accepted work substantially beyond their original commitment. Next are the Manual's reviewers whose comments contributed to improving the overall quality of the material.

The development of this manual was supported and monitored by the Office of Research and Applications of the National Oceanic and Atmospheric Administration (NOAA) under contract Number 40AANE901376.

Editorial Board

John R. Apel (1930-2001)
Global Ocean Associates, Silver Spring MD, USA

Christopher R. Jackson
Global Ocean Associates Alexandria, VA USA

Pablo Clemente-Colón
Office of Research and Applications, NOAA/NESDIS, Camp Springs, MD, USA

William G. Pichel
Office of Research and Applications, NOAA/NESDIS, Camp Springs, MD, USA

Robert A. Shuchman
Altarum (formerly ERIM), Ann Arbor, MI, USA

Christopher C. Wackerman
General Dynamics - Advanced Information Systems, Ann Arbor, MI, USA

Additional thanks to Jeannie Leggett Sikora for copy editing, Jim Haines for his spot illustration support, Laura McGinn who handled the references and BookEnd Indexing (Susan Danzi Hernandez) for developing the index.

The views, opinions, and findings contained in this report are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy or decision.

PREFACE

The objective of this Manual is to lay out, for a wide range of users, the types of information that may be obtained from SAR images of the ocean, and methods of analyzing the imagery. It is intended for non-expert but scientifically literate workers who wish to use synthetic aperture data in their studies but who do not quite know what to make of the data.

Spaceborne synthetic aperture radar (SAR) provides a unique view of the Earth's surface. The finely detailed imagery of the ocean's surface from a SAR is assuredly the most complex and least understood data provided by remote sensing instruments. The sea surface can appear featureless or contain the signatures of such diverse phenomena as surface and internal waves, upwelling, current boundaries, shallow water bathymetry, wind, rainfall, roll vortices, convective cells, storms, and a wide variety of sea ice forms.

This book is divided into four sections. The background material in the first section presents the basic properties of SAR as well as introduces the factors behind how the sea surface and sea ice are observed by radar. The remaining sections are devoted to oceanic, atmospheric and boundary layer measurements and sea ice observations. Where appropriate, information is included on how SAR is being used routinely to aid the operational mission of environmental agencies (see for example Chapters 12, 13 and 20).

One of the keys to the broad acceptance and use of SAR is educating potential users about the capabilities of the sensor. Hence the need for the creation of this Manual. It is hoped that it will prove useful to anyone interested in understanding and applying SAR imagery to their work in the marine environment.

TABLE OF CONTENTS

Preface	v
Acknowledgements	vi
Reviewers	ix
 Part I. Background	
Chapter 1. Principles of Synthetic Aperture Radar	1
Samuel W. (Walt) McCandless Jr. and Christopher R. Jackson	
Chapter 2. SAR Imaging of the Ocean Surface	25
Benjamin Holt	
Chapter 3. SAR Measurements of Sea Ice.....	81
Robert G. Onstott and Robert A. Shuchman	
 Part II. Oceanic Measurements	
Chapter 4. Microwave Scattering from the Sea	117
Donald R. Thompson	
Chapter 5. Ocean Surface Waves and Spectra	139
Paris W. Vachon, Frank M. Monaldo, Benjamin Holt and Susanne Lehner	
Chapter 6. Wave Refraction, Breaking, and Other Near-Shore Processes.....	171
Christopher C. Wackerman and Pablo Clemente-Colón	
Chapter 7. Oceanic Internal Waves and Solitons	189
John R. Apel	
Chapter 8. Ocean Currents and Current Gradients	207
David R. Lyzenga, George O. Marmorino and Johnny A. Johannessen	
Chapter 9. Upwelling.....	221
Pablo Clemente-Colón	
Chapter 10. Underwater Topography.....	245
Werner Alpers, Gordon Campbell, Han Wensink and Quanan Zheng	
Chapter 11. Oils and Surfactants.....	263
Werner Alpers and Heidi A. Espedal	
Chapter 12. Ship and Wake Detection	277
William G. Pichel, Pablo Clemente-Colón, Christopher C. Wackerman and Karen S. Friedman	

Part III. Atmospheric Boundary Layer Measurements

Chapter 13. Wind Speed and Direction.....	305
Frank M. Monaldo and Robert Beal	
Chapter 14. Marine Atmospheric Boundary Layer Cellular Convection and Longitudinal.....	321
Roll Vortices	
Todd D. Sikora and Susanne Ufermann	
Chapter 15. Mesoscale Storm Systems.....	331
Karen S. Friedman, Paris Vachon and Kristina Katsaros	
Chapter 16. Atmospheric Vortex Streets and Gravity Waves.....	341
Xiaofeng Li	
Chapter 17. Rainfall	355
Werner Alpers and Christian Melsheimer	

Part IV. Sea Ice Observations

Chapter 18. Processes at the Ice Edge—The Arctic	373
Robert Shuchman, Robert G. Onstott, Ola M. Johannessen, Stein Sandven and Johnny A. Johannessen	
Chapter 19. Antarctic Sea Ice and Icebergs	397
Robert G. Onstott	
Chapter 20. Synthetic Aperture Radar for Operational Ice Observation and Analysis.....	417
at the U.S., Canadian and Danish National Ice Centers	
Cheryl Bertoia, Mike Manore, Henrik Steen Andersen, Chris O’Connors, Keld Q. Hansen and Craig Evanego	

Appendices

A. Satellite Data and Image Products	443
B. Image Archives and Resources	451
C. SAR Frequency Bands.....	453
D. Author Contact Information.....	454
Index	457

REVIEWERS

Werner Alpers
Universität Hamburg
Institut für Meereskunde
Bundesstr. 53,
D-20146 Hamburg, Germany

Robert Beal
The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723

Cheryl Bertoia
U.S. National Ice Center,
4251 Suitland Road
Washington D.C. 20395

Robert Brown
Applied Physics Laboratory
University of Washington
1013 NE 40th St.
Seattle, WA; 98105

Timothy F. Duda
Applied Ocean Physics & Engineering Dept.
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Stephen L. Durden
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109

Steve Elgar
Applied Ocean Physics & Engineering Dept.
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Heidi A. Espedal
Nansen Environmental and
Remote Sensing Center
N-5059 Bergen, Norway

Ralph Foster
Applied Physics Laboratory
University of Washington
1013 NE 40th St.
Seattle, WA 98105

Martin Gade
Universität Hamburg
Institut für Meereskunde
Bundesstr. 53,
D-20146 Hamburg, Germany

James Gower
Institute of Ocean Sciences
PO Box 6000
9860 West Saanich Road
Sidney, BC V8L 4B2, Canada

Martin O. Jeffries
Geophysical Institute
University of Alaska Fairbanks
P. O. Box 757320
Fairbanks, AK 99775

Ron Kwok
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109

Susanne Lehner
Deutsches Zentrum für Luft- und Raumfahrt
D-82234 Wessling Germany

George A. Leshkevich
NOAA/Great Lakes Environmental Research
Laboratory
Ann Arbor, MI 48105-2945

Gad Levy
NorthWest Research Associates
Bellevue WA 98009

Charles Livingston
Radar Systems Section
DRDC – Ottawa
3701 Carline Ave.
Ottawa, Ontario K1A 0Z4, Canada

Jim Lyden
Veridian Systems Division
PO Box 134008
Ann Arbor, MI 48113-4008

David R. Lyzenga
Department of Naval Architecture and Marine
Engineering
University of Michigan
Ann Arbor, MI 48109-2145

Michael Manore
Canadian Ice Service, Environment Canada
373 Sussex Dr., E-3
Ottawa, Ontario, K1A 0H3, Canada

George O. Marmorino
Remote Sensing Division
Naval Research Laboratory
Washington, D.C. 20375

James A. Maslanik
University of Colorado
CCAR, UCB431
Boulder, CO 80309

Lyn McNutt
Geophysical Institute
University of Alaska
903 Koyukuk Drive
Fairbanks, AK 99775

William J. Plant
Applied Physics Laboratory
University of Washington
1013 NE 40th St.
Seattle, WA 98105

R. Keith Raney
The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723

Britt Raubenheimer
Applied Ocean Physics & Engineering Dept.
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Todd Sikora
United States Naval Academy
Department of Oceanography
572M Holloway Rd
Annapolis, MD 21402

John Scott
QinetiQ
Winfrith Technology Centre
Dorset, DT2 8XJ, United Kingdom

Neil R. Stapleton
QinetiQ
Winfrith Technology Centre
Dorset, DT2 8XJ, United Kingdom

Roger Sullivan
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311

Paris W. Vachon
Canada Centre for Remote Sensing
Ottawa, Ontario, K1A 0Y7, Canada

George S. Young
503 Walker Building
Department of Meteorology
The Pennsylvania State University
University Park, PA 16801

Synthetic Aperture Radar Marine User's Manual